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Research Paper

Water use of irrigated almond trees when subjected to water deficits

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ABSTRACT

Recently planted intensive almond plantations may have access to limited water supply due to water scarcity thus, information on almond water use under limited irrigation is needed. Here, the soil water balance was used to assess the consumptive use (ET) of full irrigated, moderately stressed and severely stressed almond trees over a three-year study, as well as the relation between applied water and ET. Sap flow measurements in eight experimental trees were used to obtain independent transpiration (T) measurements. Evaporation from soil (E_S) was modelled to estimate tree T from the water balance. Relative consumptive use in the deficit irrigation (DI) treatments largely exceeded the relative applied water, highlighting the need to measure ET in stressed treatments for hydrologic purposes. The moderately stressed treatments (irrigated at 65.5% of full irrigation) consumed 79.0% of maximum evapotranspiration (ET of 897 mm), while the severely stressed treatment consumed 63.6% of ETc (ET of 722 mm) when applied water was only 39.6% of control. On average, almond ETc approached 1200 mm, Seasonal evolution of the transpiration coefficient yielded maximum peak values ranging from 0.99 to 1.08, and minimum peak values of 0.33 attained with a severe deficit irrigation strategy. Transpiration measured by Compensated Heat Pulse-Calibrated Average Gradient sap-flow (x), was compared to water balance T estimates (y), and yielded a very good relation over the three years of study ($y = 0.90x + 4.23$, $r^2 = 0.81$). The sap flow measurements proved to be useful to overcome the limitations of the soil water balance technique, revealing that almond trees were able to extract water from below the monitored depths and suggesting that deep percolation event must have occurred in spring and autumn.

1. Introduction

Almond is one of the major tree crops in Spain in terms of cultivated area, 619,915 ha according to ESYRCE 2016 (MAPAMA, 2016). Although it has been grown traditionally in marginal lands under rainfed conditions, recently, irrigation has been introduced with concomitant changes for intensification of production. However, due to chronic water scarcity, Spanish Water Basin Authorities of most areas are unable to allocate irrigation water for almond production to meet its potential requirements. Thus, deficit irrigation (DI) strategies for almonds must be applied in order to reduce water consumption with a minimum impact on crop productivity (Fereres and Soriano, 2007). In order to design successful DI strategies and to assess consumptive use at the hydrologic basin scale, both the maximum crop evapotranspiration (ET_C) and the actual evapotranspiration (ETa) under different conditions of climate, soil, water availability and plantation typology must be known.

Potential crop evapotranspiration (ETc) can be measured by mass transfer or energy balance methods, and can also be estimated using models such as the Penman-Monteith equation (Allen et al., 1998). In the case of well-watered almond trees, there have been recent studies measuring ETc with eddy covariance (Stevens et al., 2012) or with a large weighing lysimeter (Espadafor et al., 2015).

There are many more difficulties in determining ETa of tree crops under field conditions. One option is to use the water balance approach to compute ETa when ET is limited by water deficits. In the case of almond trees, Girona et al. (2005), Egea et al. (2010) and Egea et al. (2013) have dealt with the responses to variable irrigation, but the ETa of stressed treatments was not measured nor calculated, as all the results were expressed in terms of applied water (AW, that

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is irrigation, Ir, plus effective precipitation, Peff). The extrapolation of these responses beyond the soil and climatic conditions where they were obtained is questionable. Recently, Spinelli et al. (2016) measured ETa of deficit-irrigated almond trees with eddy covariance, but surprisingly, they found that ETa was the same as the ETc of well-watered trees.

The goodness of a soil water balance depends on the accurate estimation of soil water depletion (SWD) by the root system. For this purpose, volumetric soil water content measured with the neutron probe method is considered to be advantageous over the use of other instrumentation such as tensiometers, FDR or TDR (Evett and Steiner, 1995). However, in all cases, the spatial variability of soil water properties (Nielsen et al., 1973) makes it necessary to seek a compromise between accuracy and practicality regarding the number of measuring points. In a drip-irrigated tree crop, the variability coming from unevenly wetted soil surface is another issue, requiring additional spatial variations in soil moisture observations. Andreu et al. (1997) described the soil moisture variability and dynamics around a single irrigated almond tree. They showed that, regardless of the depths of measurement, there is often significant uncertainty in the magnitude of the deep percolation component (DP). Nevertheless, there are a number of studies that have used the water balance approach in irrigated tree crops (Fereres et al. (1982) and Franco et al. (2000) in young almond trees; Garnier et al. (1986), Girona et al. (2002) and (Ayars et al., 2003) in peach; Klaij and Vachaud (1992) and (Kang et al., 2003) in pear; de Azevedo et al. (2003) and da Silva et al. (2009) in mango and Iniesta et al. (2008) in pistachio). Besides, the soil water balance approach has been incorporated into most crop simulation models for an array of conditions (Belmans et al., 1983; Brisson et al., 1992; Campos et al., 2016; Choudhury et al., 2013; Eitzinger et al., 2003; Phogat et al., 2017).

For determining ET from the soil water balance, one needs to quantify the water fluxes entering (namely, precipitation, P, and irrigation, Ir) and leaving (runoff, RO, and deep percolation, DP) the soil profile under study during a period spanning two soil water content (SWC) measurements. Once all the fluxes are measured or estimated, ET can be determined from the balance of inputs minus outputs. Additionally, if evaporation from soil (E_S) can be measured or estimated (Bonachela et al., 1999, 2001; Ritchie, 1972), transpiration (T) can also be known.

Sap-flow probes allow the direct estimation of tree transpiration by integrating sap flow velocity deduced from measurements of heat diffusion. Within the available sap-flow measuring methods, the Compensated Heat Pulse (CHP) has been proposed by Fernández et al. (2001) as a tool for irrigation scheduling. This technique is able to detect water stress as measured by the fall in tree transpiration relative to ETo or when a reference T value is obtained (Fernández et al., 2001; Tognetti et al., 2004, 2005). However, the azimuthal variations in sap velocity within a probed tree trunk makes calibration of sap-flow sensors highly recommended (López-Bernal et al., 2010; López-Bernal et al., 2015; Nortes et al., 2008).

There are only a few reports that combine the water balance technique with sap-flow measurements for calculating ET, such as in pines in USA (Oren et al., 1998), pear trees (Kang et al., 2002) and apple trees in north China (Gong et al., 2007).

In the context of almond production intensification under limited water supply, the objectives of this research were a) to determine the ETa of almond trees undergoing different deficit irrigation regimes, b) to relate the ETa to the level of AW, in order to assess the relevance of soil water extraction under deficit irrigation; and c) to compare the soil water balance method for estimating T against sap-flow measurements of T in almond trees.

2. Materials and methods

2.1. Experimental site and field management

The three-year experiment was conducted between 2014 and 2016 in a 5.5-ha almond (cv. *Guara*) orchard planted in 2009. Trees were grafted on G-677 rootstock and planted in a 6 × 7 m grid. The field is located at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37,8°N, 4,8°W). Trees were pruned the two first years for scaffold formation and only again in January 2016 to ease machinery traffic. There is an automated weather station about 300 m apart from the orchard, from which climate data were collected along the study. In the centre of the orchard there is one large weighing lysimeter with one almond tree (Lorite et al., 2012), which is representative of the rest of the orchard.

Cordoba climate is typical Mediterranean: hot and dry summers and mild winters; annual rainfall averages around 600 mm. The experimental soil, of alluvial origin, is deep, of sandy loam texture in the first 150 cm depth, and lighter texture in the deeper layers. The typical upper (field capacity) and lower (wilting point) limits of soil water storage are 0.23 and 0.08 cm^3/cm^3, respectively.

The experimental trees were irrigated to satisfy their full water requirements since planting until the onset of the differential irrigation treatments in 2013. The control treatment and the rest of the trees outside the experimental area were fully irrigated. Trees were daily irrigated with 12 pressure-compensating drippers (4 l/h, with 1 m distance between drippers) per tree, using two drip laterals, each about 80–100 cm away from the tree rows. In 2014, there was one water meter per treatment. In 2015, individual water meters (WS15170 DN-15-3/4, Abering, Madrid, Spain) were installed in every experimental plot. Water meter readings were collected every two weeks in the new meters, while the old ones were used for daily irrigation monitoring and management.

Soil was kept free of weeds by both mower passes and herbicide applications, and pests and diseases were controlled following a treatment calendar, which was adjustable according to each season conditions. Mineral fertilization was calculated according to University of California recommendations (http://apps.cdfa.ca.gov/frep/docs/Almonds.html), and its application followed the recommendations by Muncharaz (2003).

2.2. Experimental design

Irrigation treatments started in spring 2013, by applying different limited irrigation levels, with full irrigation supply as the control. To induce a moderate stress level, both sustained deficit irrigation and regulated deficit irrigation strategies were tested, while severe water stress was induced by a more limited RDI regime. Thus, irrigation treatments were thus planned as follows (Table 1):

2.2.1. Fully irrigated control (FI)

These trees received the water requirements (ETc) calculated as in (Fereres et al., 2012). From 2015 on, the relation between ground cover (GC) and a transpiration coefficient (K_T = T/ETo) proposed by Espadafor et al. (2015), that is K_T/GC = 1.2, was used with an added 15%, to account for the evaporation from emitters wet surfaces. The addition of 15% was calculated using Bonachela et al. (2001) model assuming tree intercepted radiation of 60% and a wetted area by emitters of 25%. By delaying the onset of irrigation, some SWC depletion by the trees was allowed early in the season to avoid deep percolation, which would be significant if applying water to the soil at field capacity after winter rains.